Geothermics 75 (2018) 180–191

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Pressure transient analysis during CO_2 push-pull tests into faults for EGS characterization

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ARTICLE INFO

Keywords:
Enhanced geothermal sites (EGS)
CO_2 push-pull
Pressure transient
Desert Peak geothermal field
Sensitivity analysis
Parameter estimation
Inverse modeling
iTOUGH2

ABSTRACT

With the goal of detecting and characterizing faults and fractures in enhanced geothermal systems (EGS), a new technology involving CO_2 push-pull testing, active-source geophysical imaging, and well logging has recently been proposed. This technique takes advantage of (1) the contrasting properties of supercritical CO_2 and water which cause CO_2 to appear distinct from surrounding brine in seismic and other geophysical logging approaches, (2) the non-wetting nature of CO_2 which keeps it localized to the faults and fractures to create contrast potentially sufficient for active seismic and well-logging approaches to image faults and fracture zones at EGS sites. In this study, we evaluate the feasibility of using pressure transient monitoring during CO_2 push-pull tests to complement active seismic and wireline well logging for EGS characterization. For this purpose, we developed a 2D model of a prototypical geothermal site (Desert Peak, NV) that includes a single fault. The fault zone consists of a slip plane, fault gouge, and damage zone, and is bounded by the surrounding matrix of the country rock. Through numerical simulation using iTOUGH2, we found that the pressure transient at the monitoring wells in the fault gouge shows unique traits due to the multiphase flow conditions developed by CO_2 injection, and varies sensitively on the arrival of the CO_2 plume and the degree of CO_2 saturation. A sensitivity analysis shows the pressure transient is most sensitive to the fault gouge permeability, but also depends on multiphase flow parameters and the boundary conditions of the fault. An inversion study reveals that the fault gouge permeability can be best estimated with the pressure transient data, whereas additional CO_2 saturation data do not improve the accuracy of the inversion significantly.

1. Introduction

Enhanced geothermal systems (EGS) are engineered geothermal reservoirs that benefit from the ability to control fracturing and fracture flow. For successful EGS, it is essential to characterize faults and fracture networks (both natural and induced) at EGS sites. To achieve this goal, a new methodology has been proposed and evaluated, which uses CO_2 push-pull testing to enhance imaging of fractures and faults at EGS sites (Borgia et al., 2015, 2017a,b; Oldenburg et al., 2016; Zhang et al., 2015). This technique involves (1) injection and withdrawal of CO_2 into/out of fault/fracture zone, (2) imaging the induced contrast with active seismic and well logging approaches, and (3) characterizing the fault/fracture zone with the complementary data provided by (1) and (2). Natural and induced faults and fractures at EGS sites are difficult to characterize using traditional seismic or well-logging imaging techniques because faults/fractures filled with ambient brine are indistinguishable from surrounding matrix at EGS conditions. Supercritical CO_2 injected for the push-pull well testing helps increase seismic contrast because of the high compressibility of CO_2, which significantly reduces the stiffness tensor and consequently seismic velocity, electrical contrast because of the low electrical conductivity of CO_2 compared to brine, and neutron capture contrast because of the displacement of water. The additional benefit of using CO_2 is that CO_2 has a strong tendency to flow in faults and fractures due to its non-wetting characteristics. CO_2 replaces the formation brine in fault/fractures and effectively increases the contrast in geophysical properties between fault/

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https://doi.org/10.1016/j.geothermics.2018.05.004
Received 15 November 2017; Received in revised form 8 May 2018; Accepted 17 May 2018

fractures and matrix while tending to resist dispersing into the matrix. The enhanced contrast in seismic and well logging arising from CO_2 saturation can be used to detect and characterize the fault/fracture zone.

In this study, we evaluated the pressure transient analysis during CO_2 push-pull to complement active seismic and wireline well logging for EGS characterization. Pressure transient testing is one of the essential tools to explore and monitor subsurface formations, and is used to infer geometric and flow properties as well as multiphase flow conditions. For this study, we developed a discretized model domain with a single dipping fault based on a highly simplified conceptual model of the Desert Peak geothermal field (Borgia et al., 2017a,b). We used TOUGH2/ECO2N V2.0 (Pruess et al., 2012; Pan et al., 2016) to simulate pressure transients during the injection (push period) and withdrawal (pull period) of CO_2 into the fault zone. We present here the characteristics of these pressure transients and examine the feasibility and effectiveness of pressure transient data interpretation for EGS characterization.

2. Geologic setting – Desert Peak geothermal field

The Desert Peak geothermal field is located in the northern Hot Springs Mountains ~80 km east-northeast of Reno, Nevada, and is within the northwest Great Basin, which is known as one of the most geothermally active regions in the USA. The Desert Peak geothermal field is largely controlled by NNE-striking, WNW-dipping normal faults (Faulds et al., 2004), and the geothermal field is on the left side of a set of parallel, closely spaced faults in these fault systems. This set of faults is linked by multiple subvertical faults of high fracture density, which are favorable for upward flow of hydrothermal fluids (Faulds et al., 2010). The reservoir temperature is measured at 207–218 °C (Faulds et al., 2010; Shevenell and De Rocher, 2005).

Fig. 1 shows the geologic map of the Deseart Peak geothermal field (modified from Faulds et al., 2012) and the cross section projecting through the central part of the Rhyolite Ridge fault zone. The geothermal field is largely composed of Miocene volcanic and sedimentary rocks that overlie a Mesozoic basement, and the range is dissected by the NNE-striking normal faults. The 2D model domain we consider is marked with a red rectangular box in the cross-section view. Details of structural and geologic features of the Desert Peak geotheraml field can be found in Faulds et al. (2010).

3. Model setup and parameters

3.1. Model development

We used TOUGH2/ECO2N V2.0 (Pruess et al., 2012; Pan et al., 2016) to develop a model and simulate the two-phase flow of CO_2 and water during CO_2 push-pull injection-withdrawal. This code is able to simulate two-phase flow in the pressure and temperature range up to 600 bar and 300 °C, respectively, and is therefore appropriate for EGS applications. Here, consistent with the terminology in TOUGH2/ECO2N, a CO_2-rich non-wetting phase is referred to as a gas phase. iTOUGH2-PEST (Finsterle, 1993; Finsterle, 2004; Finsterle et al., 2016; Finsterle and Zhang, 2011) is used for sensitivity and inverse analysis.

We developed a simplified 2D model including a single fault based on the geologic features of the Desert Peak geothermal field. We adapted and expanded the model domain originally developed by Borgia et al. (2017a,b) to explore the technical feasibility of CO_2 push-pull testing for EGS fault/fracture characterization for pressure transient analysis. Similar to the conceptual model of a fault zone from Gudmundsson et al. (2002), the fault zone in our model consists of a slip plane, fault gouge, and damage zone, and it is bounded by the surrounding country rock. The fault gouge is formed during fault slip, and this crushed rock primarily consists of breccia and other clay-size particles. The gouge may include one or multiple thin slip planes, which are characterized by finer particles, polished surfaces and striations. In general, slip planes and fault gouges have higher permeabilities than the other rock types. The damage zone refers to the fractured rock developed at the outer boundary of the fault gouge during fault −slip events and extends into the unfaulted country rock. The fault gouge, damage zone, and country rock matrix have distinct fluid-flow properties (i.e., permeability and porosity), and such differences are taken into account in our model (see Table 1). In our 2D model, the fault gouge is 5 m thick on both sides of the slip plane (10 m total), and the damage zone is 10 m thick on both sides of the fault gouge. The matrix is 200 m thick on both sides of the damage zone, which is sufficiently wide to minimize the effect of the side boundaries. The model takes into account the variable country rocks for the matrix, as color-coded in Fig. 2. Table 1 shows the hydrological properties of each structure in the model.

The z-axis of the model is aligned along the dip of the fault, and the x-axis is in the direction across the fault. The grid is discretized uniformly in the z-direction ($dz = 10$ m), and more finely in the x-direction near the slip plane (from $dx = 20$ m at the far end of the matrix down to $dx = 2$ cm for the slip plane) as shown in Fig. 2. The width of the cells in the horizontal direction parallel to the fault direction (the y-direction) is 50 m. The grid is rotated clockwise by 30° to make the fault dip 60°. The model vertically extends from the water table, which is 30 m below the ground surface, to the depth of 1435.4 m below the surface. The injection/withdrawal well intersects the fault gouge at a depth of 1193 m. Note that the 10-m height of the grid block is used for the injection/withdrawal well without any further grid refinement. Thus, the model is not intended to accurately reproduce near-wellbore effects during CO_2 injection and withdrawal. The focus of the present study is on exploring whether we can gain additional information regarding EGS fault/fractures from pressure transient data collected at offset monitoring wells during CO_2 push-pull testing.

In addition to the hydrological rock properties, Table 1 includes the parameters for multiphase flow. For the slip plane and fault gouge, the van Genuchten (1980) model is used to describe the liquid relative permeability and capillary pressure relations for the two-phase system of CO_2 and water. The maximum gas relative permeability (k_{rgmax}), which is defined as the relative permeability at the residual water saturation, is known to be typically smaller than unity (Levine et al., 2014). To take this into account in the fault gouge, where most of the injected CO_2 is expected to flow, for gas relative permeability we use the hysteretic form of the van Genuchten model (Lenhard and Parker, 1987) implemented in TOUGH2 (Doughty, 2013), which allows the user to define the maximum value of the gas relative permeability. In this study, k_{rgmax} is set as 0.5. For simplicity, hysteresis itself is turned off and the characteristic curves are the same for CO_2 drainage and imbibition. For the damage zone and matrix, where little CO_2 is expected to flow, we use the simpler Corey (1954) curves for two-phase relative permeability and the van Genuchten (1980) model for capillary pressure. Fig. 3 shows the characteristic curves of all rock types in the model.

3.2. Initial and boundary conditions

The initial hydrostatic condition is based on the water table at 30 m below the ground surface. This initial hydrostatic condition is used to calculate the pressure difference $\Delta P = P - P_{init}$, which is the variable used in this study to describe all pressure-related data. Temperature varies from 25 °C at the top boundary to 170 °C at the depth of 630 m with a geothermal gradient of 0.24 °C/m, and to 210 °C at the bottom boundary with the geothermal gradient of 0.05 °C/m, which approximately represents field observations. The impact of salinity on pressure transient is not considered, and the salinity and the initial dissolved CO_2 concentration are assumed to be zero. The top and bottom boundaries are open to flow and the side boundaries are closed.